

Dynamics of escaping Earth ejecta and their collision probability with different Solar System bodies

M. Reyes-Ruiz^{a,*}, C.E. Chavez^a, M.S. Hernandez^b, R. Vazquez^a, H. Aceves^a, P.G. Nuñez^c

^a*Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo Postal 877, Ensenada 22800, B.C., México*

^b*Facultad de Ciencias, Universidad Autónoma de Baja California, Ensenada 22860, B.C., México*

^c*Instituto de Estudios Avanzados de Baja California, Ensenada 22800, B.C., México*

Abstract

It has been suggested that the ejection to interplanetary space of terrestrial crustal material accelerated in a large impact, may result in the interchange of biological material between Earth and other Solar System bodies. In this paper, we analyze the fate of debris ejected from Earth by means of numerical simulations of the dynamics of a large collection of test particles. This allows us to determine the probability and conditions for the collision of ejecta with other planets of the Solar System. We also estimate the amount of particles falling-back to Earth as a function of time after being ejected.

The Mercury 6 code is used to compute the dynamics of test particles under the gravitational effect of the inner planets in the Solar System and Jupiter. A series of simulations are conducted with different ejection velocity, considering more than 10^4 particles in each case. We find that in general, the collision rates of Earth ejecta with Venus and the Moon, as well as the fall-back rates, are consistent with results reported in the literature. By considering a larger number of particles than in all previous calculations we have also determined directly the collision probability with Mars and, for the first time, computed collision probabilities with Jupiter. We find that the collision probability with Mars is greater than values determined from collision cross section estimations previously reported.

Keywords:

Astrobiology, Impact processes, Celestial mechanics

1. Introduction

Presently, the collision of kilometer-scale bodies with Earth, such as comets or asteroids, is believed to occur on a timescale of the order of millions of years (Chapman, 1994). Impacts by even greater bodies, with diameter of tens of kilometers, such as the Chicxulub event (Kent et al. 1981), are thought to take place approximately every 10^8 years. During the Late Heavy Bombardment (LHB) epoch of the Solar System's history, both the frequency and diameter of Earth impactors is believed to be much greater than these estimates (Strom et al. 2005).

In addition to their catastrophic effect on the diversity of life-species on Earth, giant impacts may also lead to ejecta accelerated with velocities greater than the planetary escape velocity, V_{esc} . Depending on the impactor energy, ejected debris may reach velocities significantly

higher than V_{esc} reaching Jupiter crossing orbits (Gladman et al. 2005). In the impact spallation model of Melosh (1984, 1985), material from a thin surface layer of the Earth's crust, can be lifted and accelerated to more than escape velocity by the interference of impact induced shock waves. Very low peak-shock pressures are predicted for such ejecta, offering a plausible explanation of the observed shock levels of meteors of Lunar and Martian origin.

Once material is ejected to interplanetary space, it will travel in orbits that may, depending on the ejection velocity, cross the orbits of other planets in the Solar System. Gladman et al. (2005, and references therein) have analysed the dynamics of such ejecta modelling these as a large collection of test particles. They found that, for low ejection velocities, a fraction of particles return to Earth after approximately 5000 years, between 0.6–0.2% for V_{∞} between 1 and 2 km/s, where V_{∞} is the velocity reached by the particle at very large distances from the Earth. An even smaller percentage, of

*email: maurey@astro.unam.mx

the order of 0.015% collides with Venus on a similar timescale. In principle, particles ejected with a velocity greater than the planet's escape velocity may reach Mars or even Jupiter crossing orbits. However, no collisions with either body is reported in the calculations of Gladman et al. (2005).

It has been suggested that such ejected crustal debris may carry along biologic material which may, if it collides with a suitable target, serve as seed for the development of life elsewhere in the Solar System (Mileikowsky et al. 2000 and Nicholson et al. 2000). Additionally, ejected material may return to Earth and "reseed" terrestrial life after the sterilizing effect of a giant impact has passed (Gladman et al. 2005). For this to happen, additional constraints are imposed on the time the ejecta may remain in space, as well as on the size of the crustal fragments, as these factors impact the amount of high energy radiation to which the biologic material is exposed. Wells et al. (2003) have argued that, with the current characteristics of the space environment (cosmic rays, x-rays, EUV) exposure for times greater than a few thousand years would make biological material nonviable.

In this paper, we analyse the dynamics of particles ejected from Earth in a manner similar to the analysis of Gladman et al. (2005) but improving the statistics by increasing the number of particles by more than a factor of three and using a different scheme and code to integrate the equations of motion. In section 2 we describe the numerical method used, the initial conditions and other details of our simulations. Results of the various simulations conducted are presented in section 3. In section 4 we discuss our results and we present our concluding remarks in section 5.

2. Model description

We consider ejecta as test particles moving under the action of the gravitational field of the Sun, the Moon, and all planets of the Solar System. No other forces are considered in the present study. Particles are assumed not to collide with each other, but may impact any of the massive bodies. The dynamics of the planets and test particles system is calculated using the Mercury 6.2 code developed by Chambers (1999). The code offers several integrator choices, including a hybrid integrator option which combines a symplectic integrator with a Bulirsch-Stoer scheme appropriate for when particles approach any of the massive bodies in the simulation. We have used the hybrid option of the code to follow the movement of each particle for 30,000 years (using independent integrations for each test particle). Our choice

of 30,000 years for the time that biological material can remain viable in space is adopted following Gladman (2005), who argue that unless the sensitivity of ancient microorganisms to radioactivity (the main killing factor in ejecta greater than a few meters) is 2-3 orders of magnitude greater than that of modern day bacteria, then survival times for viable biological material can range from 3,000 to 30,000 years.

The code stops the integration if the test particle collides with a planet or the Moon, if it reaches distances smaller than $1R_{\odot}$ from the Sun, or if it is ejected from the simulation domain (presently set at 40 AU). The base time step for the symplectic integrator is 24 hours, and it is decreased when the code switches to a Bulirsch-Stoer integrator during close encounters between test particles and massive objects to achieve a given accuracy. In the present simulations the change from one integrator to another is set to occur when test particles are within 3 Hill radii of a massive body.

2.1. Initial conditions

We have analyzed several cases, each consisting of 10,242 particles, set off with a given speed, V_{ej} . Particles are distributed uniformly over the surface of a sphere. To do so we use a Fuller spherical distribution (Prenis 1988 and Saff and Kuijlaars 1997), we begin with an icosahedron (by construction each of the 12 vertices of this figure is on the circumscribed sphere). An icosahedron has 30 possible lines between each point and its nearest neighbours. We take the middle point of each one of these lines and we project them into the sphere. Therefore obtaining a new figure with $30+12=42$ vertices uniformly distributed on the sphere. The general formula to obtain the number of vertices n_p is giving by the following recursive formula:

$$n_p(j) = n_{lines}(j-1) + n_p(j-1) \quad (1)$$

Where $n_p(j)$ is the number of vertices in the step j , $n_{lines}(j-1)$ and $n_p(j-1)$ are the number of lines and number of vertices in the previous step ($j-1$), respectively. It is important to notice that $n_p(1) = 12$. It can be proven that $n_{lines}(j-1) = 3n_p(j-1) - 6$. Therefore we can simplify Eq. 1 and obtain the following:

$$n_p(j) = [3n_p(j-1)-6] + n_p(j-1) = 4n_p(j-1) - 6(2)$$

Therefore, using Eq. 2 we obtain 10,242 vertices after 5 iterations, we place our particles on each one of these vertices. The points are uniformly distributed on the sphere.

The initial ephemeris of the planets-moon system is taken from the Horizons website

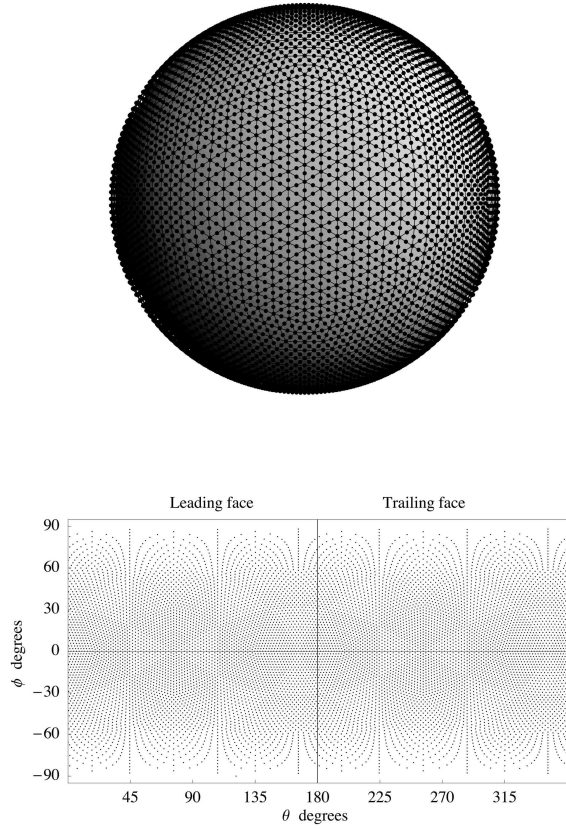


Figure 1: Initial spatial distribution of ejected particles at a height of 100 km over the surface of the planet. The bottom panel shows the initial location of particles as a function of latitude (ϕ) and “longitude” (θ (measured from the midnight meridian)).

(<http://ssd.jpl.nasa.gov/horizons>) and correspond to the configuration of the Solar System on the 6th of July 1998 at 00:00:00.0 UT. This date is the default starting date defined in the Mercury 6.2 code examples, it does not represent any special configuration of the planetary bodies and is adopted as an arbitrary initial condition. In section 4 we discuss the effect of changing the initial ephemerides on some of our results.

Test particles are set off from a height of 100 km over the surface of the Earth with an initial velocity that is purely radial. Of course, this velocity distribution does not correspond to any particular impact, as these would most likely result in the preferential ejection from one side of the planet (over a single quadrant) and ejecta with a distribution of velocities. Rather, by choosing the ejection velocity in this manner, and analysing several cases with a single ejection speed separately, we intend to sample all likely ejection conditions and iden-

tify trends indicating the effect of the ejection parameters, speed, launch position and direction. In the discussion section, we analyse the dependence of the collision probability with different bodies on the location from which a test particle is launched, although this can only be done with reasonable statistics for collisions with Earth and, to a lesser extent, with Venus and Jupiter.

According to Gladman et al. (2005), in the impact spallation theory of Melosh (1985) the cumulative distribution of ejected mass from Earth, from the escape velocity up to a given ejection velocity, is given by:

$$F(V_{\text{esc}} < V < V_{\text{ej}}) = \frac{1 - \left(\frac{V_{\text{ej}}}{V_{\text{esc}}}\right)^{-5/3}}{1 - \left(\frac{U}{2V_{\text{esc}}}\right)^{-5/3}} \quad (3)$$

where F is the fraction of the total mass ejected that leaves Earth with velocity in the range $V_{\text{esc}} < V < V_{\text{ej}}$ and U is the impactor speed. Note that the distribution is unity when $V_{\text{ej}} = U/2$, meaning that the maximum velocity with which material is ejected is one half of the speed with which the impactor collides with Earth. The distribution function for Earth-crossing asteroids or comets drops steeply as the impactor velocity increases, so that ejecta with velocity much greater than the escape velocity are even less likely to occur. The range of ejection velocities we consider correspond to impacts with speed less than 33 km/s, covering most of the asteroid and comet impacts with the Earth and Moon (Chyba et al. 1994). In the present paper we do not consider ejecta moving with even higher velocity which may result from Earth impacts by objects moving on higher velocity, comet-like trajectories.

3. Results

A series of numerical simulations with different ejection velocity were conducted, cases with low, intermediate and high ejection velocity are considered, corresponding to specific cases also reported in the study by Gladman et al. (2005). This allows a direct comparison to the results reported by these authors. We also report results for two additional cases taken at intermediate values of the ejection velocity, which do not exactly coincide with the cases studied by Gladman et al. (2005). Table 1 shows a summary of our results for each of these cases.

Neglecting the effect of the other bodies in the simulation, the ejection velocity from Earth determines the maximum apoapsis and minimum periapsis in the orbit of the ejected particles around the Sun. The maximum apoapsis is reached by particles ejected from the leading

Table 1: Description of the cases studied and summary of the number of collisions with different bodies according to our results. In parenthesis we give the percentage relative to the total number of bodies in the simulation, i.e. the collision probability.

Case	A	B	C	D	E
V_{ej} (km/s)	11.22	11.71	12.7	14.7	16.4
Earth	496 (4.84%)	106 (1.03%)	48 (0.47%)	22 (0.21%)	10 (0.1%)
Moon	2 (0.02%)	2 (0.02%)	2 (0.02%)	1 (0.01%)	0 (0%)
Venus	6 (0.06%)	17 (0.17%)	7 (0.07%)	7 (0.07%)	3 (0.03%)
Mars	0 (0%)	1 (0.01%)	1 (0.01%)	0 (0%)	0 (0%)
Jupiter	0 (0%)	0 (0%)	0 (0%)	6 (0.06%)	5 (0.05%)
Sun	0 (0%)	0 (0%)	0 (0%)	0 (0%)	19 (0.19%)
Ejected*	0 (0%)	0 (0%)	0 (0%)	254 (2.48%)	691 (6.75%)

* Particles reaching distances greater than 40 AU.

face of the planet, where the net velocity with respect to the Sun is maximum. Oppositely, particles moving in the direction opposing the motion of the planet at the moment of ejection, will have the smallest heliocentric velocity and fall to the minimum periapsis. Since the particles we are studying are launched very close to the Earth we must take Earth's gravitational potential into account. The velocity "at infinity" (V_∞) is defined as the speed that ejecta have after escaping the planet's gravitational well and is related to the ejection speed (V_{ej}) by the following:

$$V_\infty^2 = V_{ej}^2 - V_{esc}^2, \quad (4)$$

where $V_{esc} = \sqrt{2Gm_E/r_E}$, is the escape velocity from the planet, G is the gravitational constant, m_E is the mass of the Earth and r_E is the distance from the ejected particle initial position to the centre of the Earth. In the present study we adopt $r_E = 6471$ km, so that $V_{esc} = 11.098$ km/s. In order to estimate the periapsis and apoapsis we assume that the particles have already escaped the gravitational potential of the Earth and have the velocity given by Eq. (4) but since they have been launched from Earth's surface we need to add the velocity of our planet, taken as the average along its orbit, $V_E = 29.29$ km/s, so the particle velocity is given by:

$$V_{part} = V_E \pm V_\infty \quad (5)$$

In Eq. (5) we use the positive sign if the particle is ejected in the leading face and negative other-

wise. Let us assume that the Earth is in a circular orbit, then the angular momentum of the particle is given by $h = r_p V_{part}$, where r_p is the position of the particle with respect to the Sun. At the time of ejection, $r_p \approx 1$ AU, but with a velocity that is too big for staying in a circular orbit (or too small for the negative sign in Eq. (5)), the new semi-major axis and eccentricity of the ejected particle can be calculated using Eqs. (2.134) and (2.135) from Murray and Dermott (1999):

$$a = \left(\frac{2}{r_p} - \frac{V_{part}^2}{GM_\odot} \right) \quad (6)$$

$$e = \sqrt{1 - \frac{h^2}{GM_\odot a}} \quad (7)$$

where a , and e are the semi-major axis and eccentricity of the new orbit of the particle, and M_\odot is the mass of the Sun. Then for a given velocity of the particle V_{part} we can have the following maximum apoapsis (taking positive sign in Eq. (5)) and minimum periapsis (taking negative sign in Eq. (5)):

$$Q_{max} = a_{max}(1 + e_{max}) \quad (8)$$

$$q_{min} = a_{min}(1 - e_{min}) \quad (9)$$

Where a_{max} and e_{max} are calculated from Eqs. (6) and (7) using the positive sign for V_{part} and similarly

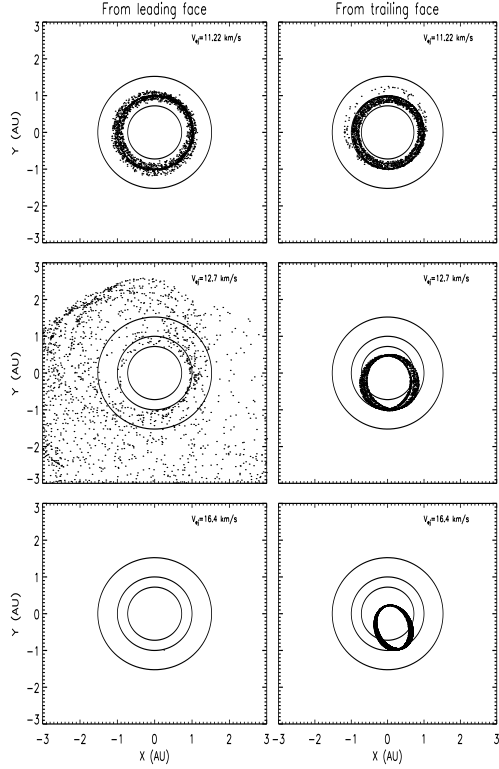


Figure 2: Projection in the $x - y$ plane of the trajectory of 2 particles, one ejected from center of the leading face of the planet, along its direction of motion (left column of panels), and the other ejected from the center of the trailing face. Dots in each panel denote the position of the particle at each of the output times of our simulations. Top, middle and bottom rows correspond to different ejection velocities, Cases A, C and E (Table 1), respectively.

a_{min} and e_{min} are calculated using the negative sign. According to these formulas, An ejection velocity of 11.62 km/s is needed to reach Mars and 14.28 km/s are required to reach the orbit of Jupiter.

Figure 2 illustrates typical trajectories followed by particles in the low, intermediate and high ejection velocity cases (A, C and E in Table 1). Shown are the orbits of 2 particles during the 30,000 years integration for each case, one ejected from the central regions of the leading face of the planet (along its direction of motion) and the other from the center of the trailing face. These cases represent extrema in the orbital energy of ejected particles and are illustrate the range of possible trajectories. Dots in each panel of Figure 2 denote the position of the particle in the $x - y$ plane at each of the output times of our simulations, separated by $\Delta t = 5000$ days.

Particles ejected with the lowest velocity considered,

$V_{ej} = 11.22$ km/s, generally remain in orbits close to that of the Earth, as shown in the top panels of Figure 2. Those ejected with the highest velocity, $V_{ej} = 16.4$ km/s (shown in the bottom panels of Figure 2), have access to a wide range of orbits. In this case, many particles, as the one depicted in the bottom left panel of Figure 2, are launched to the periphery of the Solar System and spend a very short time in the inner Solar System, hence the absence of dots in the figure.

3.1. Collision probability

As indicated in Table 1, the probability that particles collide with Earth or any other body of the Solar System, depends strongly on the velocity with which it is ejected from Earth. Particles ejected with a low velocity never cross the orbit of Mars or Jupiter, and they can only collide with Venus, the Moon or fall back to Earth.

In the context of our calculations, particles ejected with a velocity just 1% greater than the escape velocity, $V_{ej} = 11.22$ km/s (Case A in Table 1) have a maximum probability of falling back to Earth. Within 30,000 years, almost 5% of all particles fall back to Earth. Particles do not have enough energy to reach the orbits of Mars, as exemplified in the top panel of Figure 2 and hence, there are no collisions with Mars and Jupiter. There are two particles that impact the Moon, and six that impact Venus, representing 0.02 and 0.06% of the ejected population of test particles, respectively.

In Case B of Table 1, characterized by ejection velocity $V_{ej} = 11.71$ km/s, there are 106 particles that have fallen back to Earth (1.03% of the 10242 ejected particles) by the end of the 30,000 yr simulations, 2 that hit the Moon (0.02%) and 17 collide with Venus (0.17%). In contrast to case A, in case B ejected particles now have enough energy to reach Mars, and one particle collides with the planet, representing 0.01% of the ejecta. Ejection energy is still not enough to reach any of the outer planets.

As the ejection velocity increases to $V_{ej} = 12.7$ km/s, Case C, the number of particles falling back to Earth continues decreasing, in comparison to cases A and B, with only 0.47% of the 10242 particles returning to Earth. As in Case B, 2 particles impact the Moon, 7 particles collide with the planet Venus and 1 particle reaches Mars.

Of the particles ejected with conditions of case D, $V_{ej} = 14.7$ km/s, only 0.21 % return to Earth, continuing the trend observed in the previous cases. One particle impacts the Moon and 7 collide with Venus. Ejecta now can have enough energy to reach the orbit of Jupiter and many particles do so. As a result, 6 particles collide with this planet representing 0.06 % of the total number

of ejected particles. The high velocity and low gravitational pull of Mars result in the absence of collisions with Mars for this case. Also, a significant amount of particles are launched into orbits reaching the periphery of the Solar System, 254 particles travel beyond 40 AU. Purely for numerical efficiency reasons, we consider these particles as ejected from the Solar System.

Finally, only 0.1 % of the particles ejected with the maximum velocity we considered, $V_{ej} = 16.4$ km/s, ever return to Earth, no particle impacts the Moon or Mars, and only 3 particles impact Venus. A great number of particles reach the outer planets region, 5 of them colliding with Jupiter and 691 “escaping” from the Solar System (as defined above). The low orbital velocity of particles ejected from the trailing face of the planet results in about 0.2% of particles colliding with the Sun. Similarly to the previous case, no particles colliding with the planet Mars are found.

3.2. Collision time

By collision time we mean the period a particle spends in space until it collides with the Earth or any other Solar System body. In Figure 3, we illustrate the collision time for particles falling back to Earth, colliding with the Moon, with Venus, with Mars or with Jupiter, for different values of the ejection velocity (Cases A, C and E). Results are binned into 5000 year intervals with each line indicating collisions with a different body as indicated in the figure legend. It must be pointed out that in general, the number of collisions with bodies other than Earth is very small, and the trends in the time evolution of collision rates with such bodies, are of questionable statistical significance. Further studies with a greater number of ejected particles, necessary to address this issue in greater depth, are beyond the scope of the present paper.

The top panel of Figure 3 corresponds to Case A, with $V_{ej} = 11.22$ km/s. In this case, more than 2/3 of the particles returning to Earth do so in less than 20,000 years. The number of fallback particles does not decrease strictly monotonically, but less than 10% of particles return in the last time bin, between 25 and 30 kyr after ejection. Also shown in the top panel, are the collision times for particles colliding with the Moon and Venus. The numbers shown in the figure are 10 times the actual values, which are too small to be plotted. A few of the particles colliding with Venus do so after less than 15 kyr but the majority take more than 20 kyr to reach the planet.

The middle panel of Figure 3 shows the collision times for particles ejected with $V_{ej} = 12.7$ km/s, Case B discussed above. The number of particles falling back to

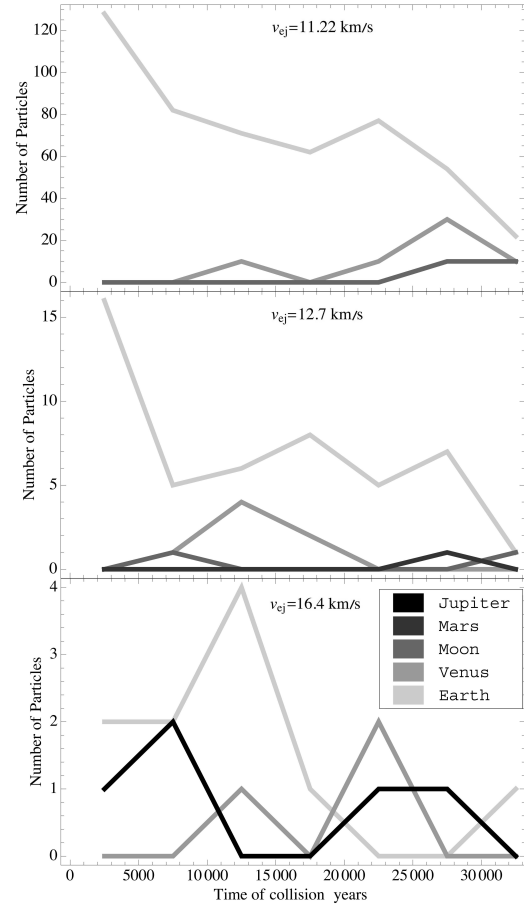


Figure 3: Collision time for particles ejected with $V_{ej} = 11.22$ km/s, binned into 5000 yr intervals. Shades of gray correspond to particles falling back to Earth, colliding with the Moon, Venus Mars or Jupiter, as indicated in the Figure legend. Note that to make the plot clear, the values corresponding to collisions with Venus and the Moon in the top panel are 10 times their real value.

Earth peaks at early times, approximately 15% of particles return in the first 5000 years. The fall-back rate more or less remains constant after this and for the next 25 kyr. Only two particles collide with the Moon and they do so at widely different times, the first one after less than 10 kyr and the second one at the very last time bin, after 25 kyr. The single particle that hits Mars does so near the end of our simulation, after 20 kyr. All particles travelling to Venus do so in less than 20 kyr, with the peak in the collision time to the planet between 10 and 15 kyr.

Finally, collision times for particles ejected from Earth with $V_{ej} = 16.4$ km/s are shown in the bottom panel of Figure 3. Only a few particles fall-back to Earth, the peak in the number of these is between 10

and 15 kyr and by 20 kyr, 90% of the particles that do so, have returned to Earth. Only 3 particles collide with Venus, 1 of these impacts after less than 15 kyr and the rest do so before 25 kyr. Of the 5 particles reaching Jupiter, a group representing 40% of the colliders do so within just 10 kyr after being ejected, the remaining 60% collide with Jupiter towards the end of the simulation.

4. Discussion

Gladman et al. (2005) has performed a similar calculation to the one conducted in this paper using a different numerical code, initial conditions and a smaller number of test particles in each simulation. In general, our results agree well with those they report. Two notable exceptions, most likely attributable to the greater number of test particles we follow in our simulations, are that we find collisions with Mars, one particle in Cases B and C, and also, we find collisions with Jupiter, 0.06% of all ejecta in Case D and 0.05% in Case E. Using an Öpik collision probability calculation, Gladman et al. (2005) estimated the collision rate with Mars to be about 2 orders of magnitude lower than found on the basis of our simulations. However, as also noted in their paper, our results for Mars are within the known typical errors of such probability estimations. No collisions with Jupiter are reported in Gladman et al. (2005).

Both results, definite collisions with Mars and Jupiter, are of astrobiological significance, owing to the possible presence of life sustaining environments in early Mars and in Jupiter's moons Europa and Ganymedes. Also worth noting is the fact that the single particle colliding with Mars, does so towards the end of our simulation, between 25 and 30 thousand years after being ejected from Earth. Collisions with Jupiter are characterized by a wider range of collision times, one half reaching the giant planet in less than 10,000 years. In future studies we will extend our analysis of both cases to determine the statistical significance of these results.

4.1. Effect of the Moon

In order to estimate the effect of the presence of the Moon on the dynamics of ejecta, we have performed a simulation with exactly the same initial conditions and run parameters as Case D (Table 1), but, as is done in Gladman et al. (2005), assuming that the Earth and the Moon are integrated into a single body with the combined mass and located at the center of mass of the system. Only minor differences in the results are found, in comparison to Case D with the Earth and the Moon

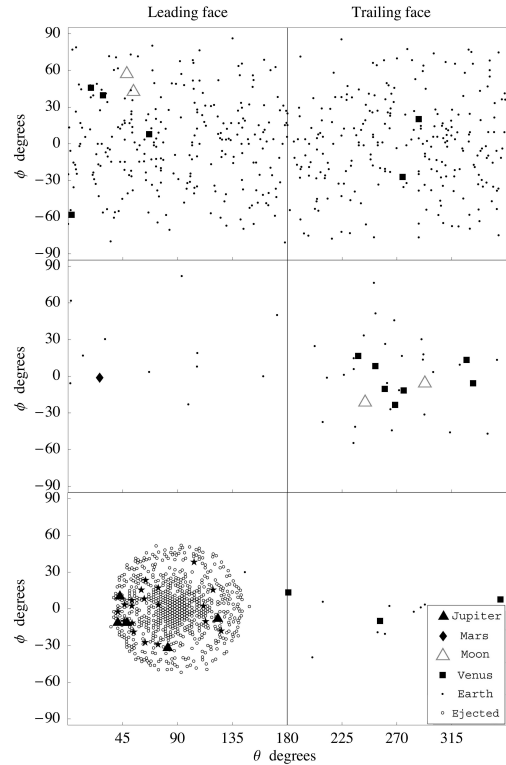


Figure 4: Initial location of particles that collide with different bodies in our simulation. Angle ϕ is the latitude of the launch position for each particle, θ is a longitude like angle but measured from the midnight meridian. The top panel corresponds to colliding particles ejected at low velocity (Case A), the middle panel corresponds to intermediate ejection velocity (Case C) and the bottom panel shows the initial location of colliding particles in the highest ejection velocity considered (Case E). The figure legend at the bottom right corner indicates the body with which a particle collides.

as separate bodies. In the single body Earth-Moon simulation, 23 particles fallback to the Earth-Moon (22 in Case D), 8 particles impact Venus (7 in Case D), 4 collide with Jupiter (6 in Case D) and 2 reach the Sun (0 in Case D). A small difference is also found in the number of particles “ejected” from the system, 220 in this case (254 in Case D).

4.2. Effect of ejection location

In Figure 4, we plot the distribution of launch positions of fall-back and colliding particles. Each panel depicts the initial latitude (angle ϕ) and a longitude-like angle (θ is measured from west to east but starting from the midnight meridian at the time of ejection). For example, the point $\phi = 0$ and $\theta = 90^\circ$ corresponds approximately to the center of the leading face along the direction of motion of the planet.

The top, middle and bottom rows of Figure 4, show the initial location of particles ejected with $V_{ej} = 11.22$, $V_{ej} = 12.7$ and $V_{ej} = 16.4$ km/s, Cases A, C and E, respectively. No clear asymmetry is found in the distribution of ejection locations for particles falling back to Earth in the case with $V_{ej} = 11.22$ km/s. This can be understood from the fact that ejecta with such a low velocity remain in orbits which are very close to Earth, as illustrated in Figure 2, thus increasing the chance of collision. As expected, there is also no asymmetry with respect to the equator. The slight asymmetries in the ejection location for particles eventually colliding with Venus and the Moon, are probably not statistically significant, and must be tested in future simulations with an even greater number of particles.

In the case with intermediate ejection velocity, $V_{ej} = 12.7$ km/s, shown in the middle panel of Figure 4, the number of particles falling back to Earth is slightly higher for those ejected from the trailing face, since orbits of these particles are less dispersed, i.e. more concentrated in the vicinity of the Earth, than for particles ejected from the leading face (see Figure 2). For the same reason, we also find that particles ejected from the trailing face are more likely to impact Venus. The opposite is true for particles traveling to Mars, as ejecta from the trailing face in this velocity range do not have enough energy to reach the planet.

The highest ejection velocity we consider, $V_{ej} = 16.4$ km/s, leads to ejecta capable of traveling outside the planetary region of the Solar System. We label these particles as ejected since they spend a very short amount of time in the inner Solar System, so that their collision probability with other planets is negligible. These are shown in the bottom panel of Figure 4 and they arise exclusively from the leading face of the planet. A similar asymmetry in the ejection location is found for particles colliding with Jupiter, since only particles ejected with a high total velocity are capable of reaching the planet. A few particles are found to fall-back to Earth and to collide with Venus, mostly ejected from the trailing face.

These results suggest that the probability of collision with different Solar System bodies of Earth ejecta resulting from a giant impact, is clearly dependent on the particular place on Earth where the collision occurred. Impacts on the leading face of the planet along its direction of motion, which are statistically more likely, lead to ejecta that have a higher probability of colliding with Mars and Jupiter.

4.3. Effect of initial ephemeris

We have also performed a simulation with the same ejection velocity as Case A, but using a different initial

ephemerides for the planets, corresponding to an initial time 6 months after the start of the rest of the simulations reported in this paper. This allows us to determine whether the initial planet configuration has a significant effect on the dynamics of ejecta and the resulting collision probabilities. Only small differences in our results are found in comparison to Case A. In the case of an initial ephemerides taken 6 months later than that considered in Case A, 531 particles fallback to Earth (496 in Case A), 8 particles impact Venus (6 in Case A) and 1 reaches the Moon (2 in Case A). A difference of 7% in the number of particles returning to Earth is found as a result of the different initial planetary configuration. The statistical significance of the differences in the number of collisions with the Moon and Venus, must be verified in future simulations with a greater number of ejected particles.

5. Conclusions

We have computed the trajectory of an ensemble of particles representing ejecta from Earth, resulting from the giant impact of a comet or asteroid, in order to determine the collision probability with different Solar System bodies. Several ejection velocities, representing the different ejecta components in a given impact, as well as different initial planetary configurations, have been explored with simulations over a period of 30,000 years. In agreement with previous work (Gladman et al. 2005) we find that ejecta can collide with the Moon, Venus or fallback to Earth after a period of several thousand years in space. A novel result in our simulations is finding particles that collide with the planet Mars, for intermediate ejection velocities, and also with Jupiter, for high ejection velocity.

Of course, a given impact will give rise to ejecta with a wide spectrum of velocities, the maximum determined by the speed of the impactor as it hits the Earth. This, together with other characteristics of the impact, also defines the amount of material ejected to space. In general, most of the escaping material does so with a velocity slightly greater than the Earth's escape velocity, the number of particles ejected drops rapidly as ejection velocity increases (Eq. (1)). Hence, the calculation of the net collision probability with a given Solar System body, must take into account the sharply decreasing velocity distribution of ejecta.

On the basis of our results, and considering the rule of thumb that the maximum ejection velocity is one half of the impactor speed, we must conclude that: 1) In collisions with impactor speed greater than $2 V_{esc}$, a significant amount of material, of the order of a few per-

cent, will fall back to Earth after remaining in interplanetary space for less than 30 kyr, 2) Ejecta transfer to Venus and the Moon can occur as long as $U \gtrsim 2V_{\text{esc}}$, 3) Ejecta transfer to Mars requires an ejection speed only slightly greater, less than 5% more, than the escape velocity and 4) The transport of terrestrial crustal material to the vicinity of Jupiter requires an impactor speed of almost 3 times the escape speed, and can occur only if the impact is on the leading face of the planet as it orbits around the Sun.

A more detailed calculation of the collision probability, taking into account the velocity distribution of ejecta, as well as computations with a greater number of particles to estimate statistically significant collision rates with the Moon, Mars and Jupiter, will be the subject of future contributions.

Acknowledgements

The authors acknowledge support from research grants IN109409 of DGAPA-UNAM and CONACYT-México grant No.128563.

References

- Chambers, J.E. 1999, A hybrid symplectic integrator that permits close encounters between massive bodies, *MNRAS*, **304**, 793-799.
- Chapman, C.R., 1994, Impacts on the Earth by asteroids and comets: assessing the hazard, *Nature*, **367**, 33.
- Chyba, C.F., Owen, T.C., Ip, W.-H., 1994, Impact Delivery of Volatiles and Organic Molecules to Earth *in* Hazards due to comets and asteroids, eds. T.Gehrels, T., M.S.Matthews. and A.Schumann, University of Arizona Press, Tucson, p.9.
- Gladman, B., Dones, L., Levison, H.F., Burns, J.A., 2005, Impact Seeding and Reseeding in the Inner Solar System, *Journal of Astrobiology*, **100**, 234.
- Kent D.V. et al., 1981, Asteroid Extinction Hypothesis, *Science*, **211**, 653-656.
- Melosh, H.J., 1984, Impact ejection, spallation, and the origin of meteorites, *Icarus*, **59**, 234-260.
- Melosh, H.J., 1985, Impact cratering mechanics - Relationship between the shock wave and excavation flow, *Icarus*, **62**, 339-343.
- Mileikowsky, C. et al. 2000, Natural transfer of viable microbes in space. 1. From Mars to Earth and Earth to Mars, *Icarus*, **145**, 391-427.
- Murray, C.D., Dermott, S.F., 1999, *Solar System Dynamics*, Cambridge Univ. Press, Cambridge. Reviews, **64**, 548-572.
- Prenis, J., 1988, *The Dome Builder's Handbook: No. 1*, Running Press, U.S.
- Saff, E.B., Kuijlaars, A.B.J., 1997, Distributing many points on a sphere, *The Mathematical Intelligencer*, **19**, 5.
- Strom, R.G., Malhotra, R., Ito, T., Yoshida, F., Kring, D. A., 2005, The Origin of Planetary Impactors in the Inner Solar System, *Science*, **309**, 1847-1850.
- Wells, L.E., Armstrong, J. C., Gonzalez, G., 2003, Reseeding of early earth by impacts of returning ejecta during the late heavy bombardment, *Icarus*, **162**, 38-46.